Doppler Lidar System Design via Interdisciplinary Design Concept at NASA Langley Research Center – Part III

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ABSTRACT

Optimized designs of the Navigation Doppler Lidar (NDL) instrument for Autonomous Landing Hazard Avoidance Technology (ALHAT) were accomplished via Interdisciplinary Design Concept (IDEC) at NASA Langley Research Center during the summer of 2013. Three branches in the Engineering Directorate and three students were involved in this joint task through the NASA Langley Aerospace Research Summer Scholars (LARSS) Program. The Laser Remote Sensing Branch (LRSB), Mechanical Systems Branch (MSB), and Structural and Thermal Systems Branch (STSB) were engaged to achieve optimal designs through iterative and interactive collaborative design processes. A preliminary design iteration was able to reduce the power consumption, mass, and footprint by removing redundant components and replacing inefficient components with more efficient ones. A second design iteration reduced volume and mass by replacing bulky components with excessive performance with smaller components custom-designed for the power system. The existing power system was analyzed to rank components in terms of inefficiency, power dissipation, footprint and mass. Design considerations and priorities are compared along with the results of each design iteration. Overall power system improvements are summarized for design implementations.

Keywords: ALHAT, Doppler Lidar, IDEC, Langley, LARSS

1. INTRODUCTION

The current NDL power system has not been greatly modified for several years. The current power system uses components which are either non-optimal in terms of power consumption, or bulky and much more capable than they need to be. Optimization of the power system is two-fold: first identifying where changes would improve system performance, and then implementing these changes. Multiple Design and Analysis Cycles (DACs) were performed on the current NDL power system to reduce power, mass, and volume. Support hardware consisted of the power system, the structural system (which includes the case, racks, and other structural assemblies), and the thermal management system (which includes the cooling fans and heat sink). The support hardware was responsible for 55.8 % of total power dissipation, 65.2 % of the overall mass, and 94.5 % of the overall volume. Project goals were to reduce NDL power dissipation by 20 %, NDL mass by 15 %, and NDL volume by 20 % through optimizing the support hardware; this translates into cutting support system power dissipation by 36 %, support system mass by 23.0 %, and support system volume by 21.2 %. DAC 1 achieved these goals by removing redundant or unnecessary components, and replacing inefficient or large parts with more efficient, smaller off-the-shelf components. DAC 2 further reduced the NDL‘s system resource use with an emphasis on eliminating excess capacity in the power system. This was achieved through custom DC-DC converter designs tailored for their specific applications. This reduced power dissipation, mass, and volume, but more importantly enabled the structural and thermal management systems to be optimized in ways that would not otherwise be possible.

2. CURRENT DESIGN

The current power system transforms an input voltage source into various output voltages needed by individual devices in the electronics chassis. The external voltage source is a battery with a voltage between 18 V and 36 V, and a nominal

voltage of 28 V. Since the line running from the battery to the power system acts as an antenna, the electromagnetic interference (EMI) must be filtered out. As a result, the power system consists of two different types of components: EMI filters and DC-DC converters.

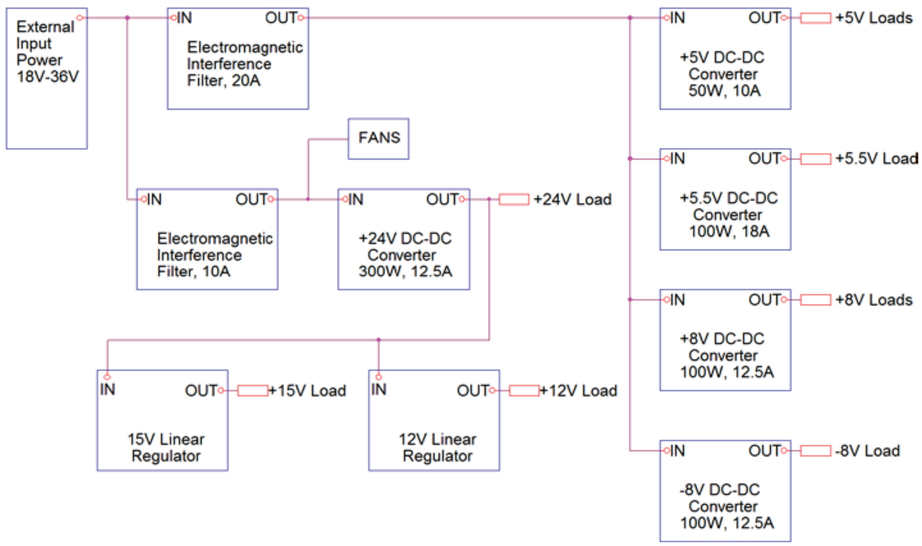

Figure 1 Original NDL power system block diagram

Figure 1 shows a block diagram of the current power system. The power system consists of two main subcircuits. The top circuit consists of a 20 A EMI filter that filters the input voltage, then feeds it to a +5 V, +5.5 V, +8 V and -8 V DC-DC converters on the far right. These converters then transform the filtered input voltage to their rated voltage and provide the transformed voltage to their respective loads. The lower circuit consists of a 10 A EMI filter that filters the input voltage, then passes the filtered input to the chassis cooling fans and a +24V DC-DC converter. This +24 V DC-DC converter supplies voltage for a +24 V load, and also supplies two linear regulators: a +12 V regulator, and a +15 V regulator. These linear regulators provide their rated voltage to their loads.

3. DESIGN ANALYSIS

To determine where effort would be most effective, where power dissipation, mass, and volume are concentrated in the current power system needed to be analyzed. Since the electrical components are generally of uniform thickness, volume is directly proportional to the circuit footprint area and volume goals will be scaled accordingly. Footprint is also of interest because the power system will have to be directly mounted to the NDL's heat sink, and decreasing this quantity will not only reduce the size (and thus mass) of the heat sink required, but also make arranging the NDL's components on the heat sink much easier. This allows the chassis to be more tightly packed, reducing the volume of the NDL. Finally, since the NDL had been modified several times since the last overhaul of the NDL power system, every individual component of the power system needed to be examined to determine if it was still needed and whether it had excessive capacity with respect to the demands of the current iteration of the NDL. This analysis would produce a list of actions that would be necessary to optimize the power system. These actions could be organized into multiple design iterations, with the most effective actions occurring in DAC 1, and the remaining actions occurring in the following design iterations such as DAC 2.

The existing NDL power system was modeled using efficiency values from power system component datasheets, measured nominal current load draws, and the design specifications for minimum and maximum load current draws for every load. The model predicted the power system's power dissipation to match well with the measurement found in the ALHAT Doppler Lidar Technology Maturation Plan. It should be noted that these two values and all other values cited in the electrical analysis assumed no power was being drawn by the cooling fans, since the power drawn by fans mostly varies due to unrelated changes in the thermal management system. This is a reasonable assumption because each fan

only adds 400 mW of power dissipation to their "upstream" EMI filter, and changes in converter performance or topology do not alter this offset. This is largely due to the very high efficiencies of the EMI filters used. Figure 2 shows the distribution of inefficiency, power dissipation, mass, and footprint within the current power system during nominal operation.

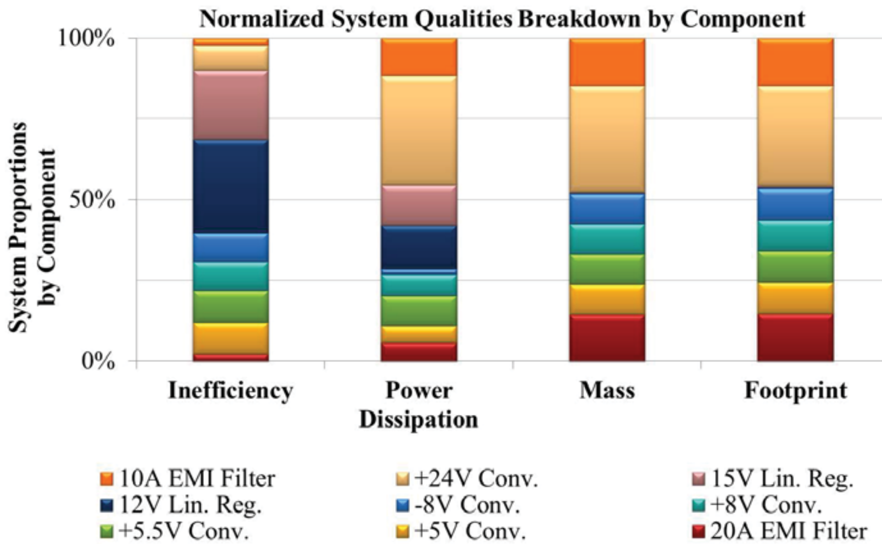

Figure 2 System resource distribution in the original NDL power system

Examination of Figure 2 reveals that the +24 V DC-DC converter is the component with the highest power dissipation, mass, and footprint in the power system. Unfortunately, the efficiency of the +24 V converter is fairly high, so replacement of this component with more efficient component is impractical. However, further investigation revealed that the +24 V converter's only load (aside from the linear regulators) had an internal DC-DC converter rated for the input voltage range. This means that the +24 V DC-DC converter was completely redundant. Removal of the +24 V converter was a simple fix, and would cut power dissipation, mass, and footprint by more than 25%.
Figure 2 also shows that the two most inefficient components in the power system are the +15 V and +12 V linear regulators. This is to be expected, since linear regulators are extremely inefficient. Figure 2 also shows that the linear regulators are responsible for approximately 25 % of the power system's power dissipation during nominal operation, so replacing the linear regulators with more efficient step-down "buck" converters would substantially cut power dissipation. Furthermore, this is a fairly simple task because there are small off-the-shelf modules available.
Inspection of Figure 2 shows that the two EMI filters are responsible for approximately 15 % of the power system's mass and footprint, respectively. Since EMI filtering of the input voltage is required, these components cannot be removed completely. However, the total current draw of the NDL with all loads at maximum operation is under 19 A and the current power system topology uses two EMI filters: a 10 A EMI filter and a 20 A EMI filter. It was interesting that the power system had two EMI filters, when one of the filters used would be fully capable of carrying the NDL's worst-case load current. Further investigation revealed that the 10 A EMI filter was a legacy of a previous design which attempted to enable both branches to be powered independently. As a result, the 10 A filter was unnecessary, and could be removed. This simple modification didn't affect power dissipation, but cut mass and footprint by approximately 15 %.

Examination of Figure 2 shows that, if the 10 A EMI filter and the +24 V DC-DC converter are removed, then the +5 V, +5.5 V, +8 V, and -8 V DC-DC converters are approximately 75 % of the remaining mass and circuit footprint. Further inspection of the maximum load current requirements and the DC-DC converter device specifications revealed that the +5 V, +8 V, and -8 V converters had safety margins in the maximum load current far in excess of what is accepted as prudent design practice. As an example, the -8 V converter load's design specification for maximum current draw was 200 mA, but the converter used was rated to supply 12.5 A. This safety margin is over 6000 %, with more than 12 A of variance before overcurrent limiters activate. The ability to supply this kind of power comes at the price of a

considerable increase in mass and footprint. As a result, replacing the +5 V, +8 V, and -8 V DC-DC converters with components that are smaller (albeit less capable) would decrease the mass and the footprint of the system considerably. Figure 2 also reveals that the power dissipation in these converters is substantially less than 25 % of the total power dissipation of the power system. This indicates that a minor decrease in efficiency would not increase power dissipation significantly; therefore, decreases in efficiency are an acceptable design tradeoff for reduced footprint. Similarly, replacement modules could be tailored to the system requirements, and optimized for decreased size; however, this is a significantly more complex task than the previous solutions.

Finally, Figure 2 shows that the +5.5 V DC-DC converter is the power system component with the highest power dissipation if the linear regulators, the unnecessary EMI filter, and the redundant +24 V DC-DC converter are ignored. This converter also has the lowest efficiency, if the linear regulators are ignored. However, since the +5.5 V converter has an efficiency on the order of 80 %, increasing efficiency is not as simple for this component as it was for the linear regulators. The +5.5 V load draws a rectangular pulse wave with a large peak current, although the average current is comparable to the other loads in magnitude. Unfortunately, the +5.5 V converter is just as large and heavy as the +5 V, +8 V, and -8 V DC-DC converters, and the same logic motivates reducing the +5.5 V converter's mass and footprint. The current converter used is rated for the power dissipated for the case where that the load is drawing the required peak current as a DC load, not for the power dissipated when operating in a pulsed mode. Similar to the previous converters, this results in a power dissipation capability that is much greater than what is called for by the application, and this unneeded capability comes at the price of greater component mass and footprint. Unlike the other DC-DC converters, however, the power dissipated by this component makes reduced efficiency an unacceptable design tradeoff. This shows that creating a design which is smaller and more efficient is a non-trivial task.

From this analysis, several actions have been identified that will reduce the NDL power system's power dissipation, mass, and volume. These tasks can be grouped into two categories: simple tasks like removal of components or replacing existing components with off-the-shelf modules, and more involved tasks like replacing components with custom designs created for their specific application. While this could be used to define the tasks that comprise the two Design and Analysis Cycles, the modifications defining each DAC were instead grouped by the estimated effect of each action, with the half of the tasks predicted to have the most effect composing DAC 1, and the remaining tasks composing DAC 2. In this case, however, both criteria would have produced the same design.

4. DAC 1 POWER SYSTEM DESIGN AND ANALYSIS

The previous analysis identified eight modifications that would reduce the power dissipation, mass, and footprint of the NDL's power system. Four of these eight modifications were estimated to have a large effect as well as being simple in nature. The two linear regulators were found to be both very inefficient and dissipating a considerable amount of power, and replacing them with more efficient components would decrease power dissipation. The +24 V DC-DC converter was the component with the highest mass, footprint, and power dissipation, but analysis showed that it was redundant. Removal of the +24 V converter would reduce the power system's mass, footprint, and power dissipation by more than any other possible action. Finally, the 10A EMI filter had the second highest mass and footprint, but analysis revealed that it was redundant, and removal of this component would substantially reduce mass and footprint. These four modifications compose the first redesign iteration DAC 1.

The design process of DAC 1 was fairly straightforward. The actions required were to remove the +24 V DC-DC converter, remove the 10 A EMI filter, replace the linear regulators with more efficient components, and reroute the outputs of the removed components so that they would have a filtered +28 V input voltage. Figure 3 is a block diagram of the DAC 1 design.

The removal of the 10A EMI filter and +24 V DC-DC converter required rerouting their loads. The loads of the +24 V DC-DC converter are the Command and Data Handing (C&DH) and both linear regulators. Routing the linear regulators and the C&DH off of the 20 A EMI filter's output voltage will provide these loads with the filtered input voltage require. Other than the +24 V DC-DC converter, the 10 A EMI filter's only load is the NDL's cooling fans. The fans can be routed off of the 20 A EMI filter's output voltage just like the linear regulators and C&DH.

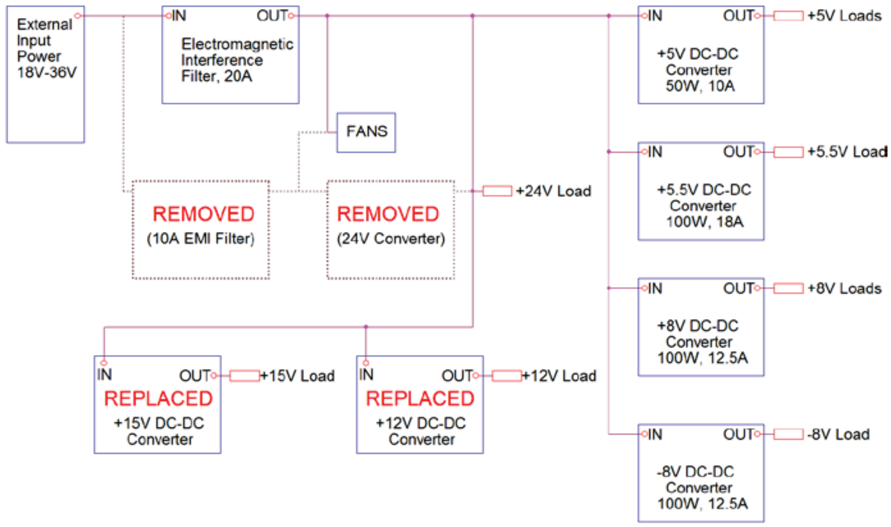

Figure 3 Block diagram of DAC 1 modification of NDL power system

A Recom R-78C12-1.0 and a R-78C15-1.0 were chosen to replace the +12 V and the +15 V linear regulators, respectively. These components are step-down "buck" DC-DC converters. The R-78 series of components was chosen because it is designed as a drop-in replacement for the LM78 series linear regulators, which were the linear regulators used in the original design. These components also meet the EN55022 Class B EMI standard when paired with a couple of capacitors to act as filters. The Class B specification was required by the DAC 1 design requirements because some of the mission hardware's vulnerability to EMI.

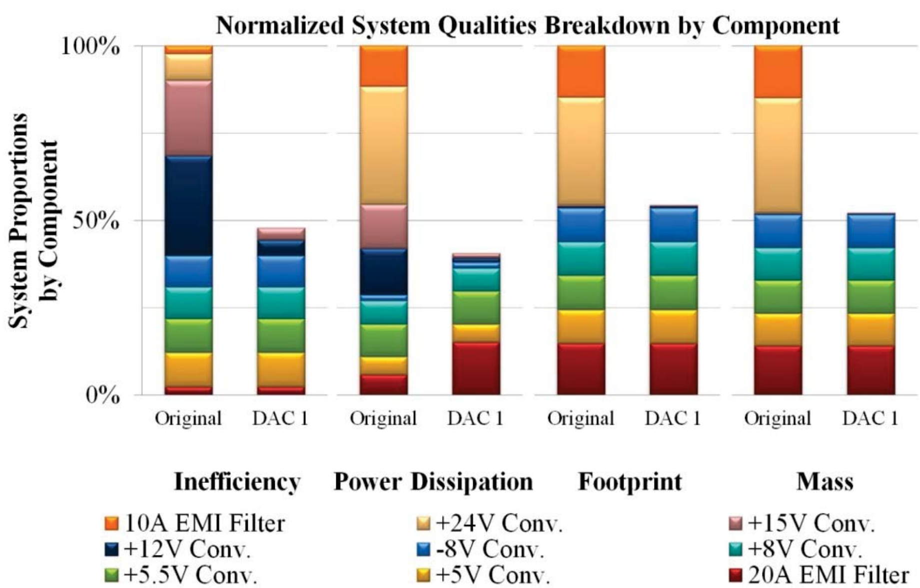

Figure 4 Comparison of system resource distribution between the original and the DAC 1 NDL power system

Figure 4 shows the change in system resource use. As with the original model, all of this presumes that the fans are drawing no current. The DAC 1 NDL power system's power dissipation, mass, and footprint are 41 %, 52 %, and 55 % of the original's, respectively. This corresponds to reductions in power system power dissipation, mass, and footprint of 59 %, 48 %, and 45 %, respectively. Since the project's goals were to reduce power system power dissipation by 36 %, power system mass by 23.0 %, and power system footprint by 21.2 %, DAC 1 far exceeded the project requirements.

5. DAC 2 POWER SYSTEM DESIGN AND ANALYSIS

The previous analysis identified eight modifications to reduce the power dissipation, mass, and footprint of the NDL's power system. The most significant four of these eight modifications were enacted in DAC 1, and the remaining four comprise the second redesign iteration of the NDL power system, DAC 2. Inspection of Figure 4 shows that the four remaining issues and solutions proposed during the analysis in Section 3 are still valid. The +5 V, +8 V, and -8 V DC-DC converters have redundancy in their device current limits, which consumes unnecessary mass and footprint. The +5.5 V design also uses a large fraction of power system mass and footprint, but this component has both the lowest remaining efficiency and second highest power dissipation. The +5 V, +8 V, and -8 V converters should be replaced with custom designs which minimize mass and footprint, and small decreases in efficiency were acceptable as a design tradeoff for these three converter designs. The +5.5 V DC-DC converter should be replaced with a custom design that decreases mass and footprint, and increases efficiency.

The DAC 2 NDL power system is a modification of the DAC 1 NDL power system design. The DAC 2 design replaces the +5 V, +5.5 V, +8 V, and -8 V DC-DC converter modules shown in Figure 3 with custom-designed DC-DC converters. Figure 5 shows the block diagram of the DAC 2 design.

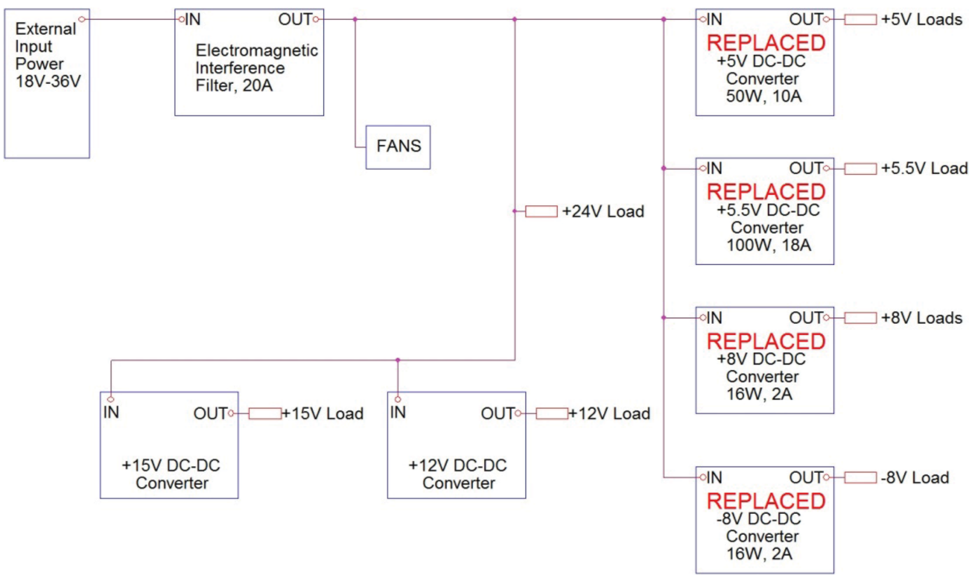

Figure 5 Block diagram of DAC 1 modification of NDL power system

The replacement design for the +5 V converter used a Vicor PI3302 step-down converter controller. One of the +5 V loads required very tight regulation of the converter's output voltage over a wide temperature range. A Point of Load (PoL) type scheme was considered, but a monolithic source was used instead. A PoL layout would have avoided the technical challenge of supplying large currents while maintaining tight load regulation over a large temperature range through the use of a single, very tightly-regulated converter for the voltage-sensitive, relatively low current-draw load and a separate converter for the other loads. However, this solution would have had considerably higher footprint and mass than the monolithic scheme, if one could be found which satisfied the design requirements. A monolithic design was found that met the design requirements and was superior in footprint to the PoL scheme. This reduced the footprint and mass of the converter further, and the estimated minimum efficiency increased to 85 %.

The replacement design for the +5.5 V converter used two Vicor PI3302 step-down converter controllers operating in parallel. This converter's design requirements required that the design be able to supply a rectangular pulse wave load current with a high peak current. The design is capable of meeting these requirements, and is not burdened by the extra mass and footprint that would be required to dissipate the heat generated by a DC current the size of the load's peak current. A worst-case estimate was made for the footprint and mass that provided a generous margin of error to account for possible future rearrangements in printed circuit board (PCB) layout to decrease EMI emissions, if necessary. This

was particularly important in this case, due to the large amounts of EMI generated by square wave currents with large amplitudes. Even according to these estimates, however, the estimated minimum efficiency increased to 91 %.

The replacement design for the +8 V converter used a Texas Instruments LM5575MH step-down converter. The loads of this converter required a low output voltage ripple (OVR). A worst-case estimate was made for the footprint and mass that provided a generous margin of error to account for possible future rearrangements in PCB layout to decrease EMI emissions, if necessary. According to these estimates, the estimated minimum efficiency increased to 90 %.

The replacement design for the -8 V converter used a Texas Instruments TPS84259 step-down converter. The loads of this converter required a low OVR. Similarly, a worst-case estimate was made. According to these estimates, the estimated minimum efficiency decreased to 80 %; however, this was deemed an acceptable design tradeoff, especially considering the relatively small amount of power flowing through the -8 V converter.

Throughout the course of the redesign, steps were continuously taken to minimize EMI because several components were sensitive to it. Zero-voltage switching (ZVS) converters were preferred over converters using hard-switching due to the lower EMI generated by this topology [9]. Where this was not possible, DC-DC converter switching frequency was kept as low as possible. High frequency coupling to ground was also implemented using decoupling capacitors to reduce high frequency common-mode EMI. Additional techniques for EMI reduction were incorporated into PCB layout, such as proper use of ground planes and minimization of AC current-loop area [10].

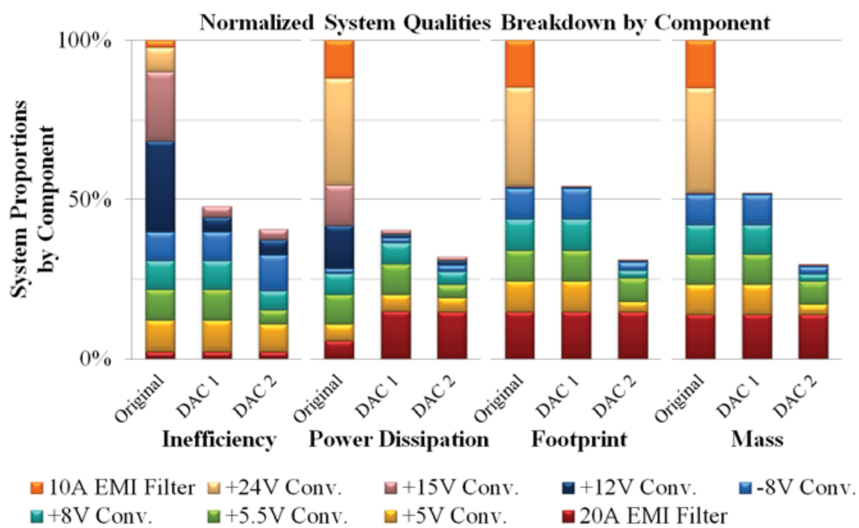

Figure 6 Comparison of system resource distribution between the original, DAC 1, and DAC 2 NDL power systems

Figure 6 shows the change in system resource use. Since the project's goals were met in DAC 1, DAC 2 aimed to meet the stretch goal of reducing system resource use by 65 %. As with the original model, all of this presumes that the fans are drawing no current. The DAC 2 NDL power system's power dissipation, mass, and footprint are 32 %, 32 %, and 30 % of the original's, respectively. This corresponds to reductions in power system power dissipation, mass, and footprint of 68 %, 68 %, and 70 %, respectively. As a result, DAC 2 met the project's stretch goals.

6. ELECTRICAL-RELATED IDEC OPTIMIZATION

Interdisciplinary interaction and cooperation via IDEC was used to great effect in multiple instances, both to address issues that arose due to the power system and to optimize the NDL chassis as a whole. The main cross-pollination that occurred was between the electrical aspects of the design and the thermal analysis, utilizing mechanical component placement to help address potential EMI sources, and setting electrical design requirements and design priorities to enhance mechanical (paper Part I) and thermal optimization (paper Part II).

Early in the redesign process, it was evident that the overall reduction in system resource use due to optimization of the power system would be insufficient to meet project goals, if not insignificant, when viewed in isolation. The power dissipation due to the inefficiencies inherent in the power system only amounts to less than 23 % of the support system total. Mass was even worse, with the mass of the power system being a mere 5 % of a total support system mass, and an even lower proportion of support system volume. This meant that <u>electrical optimization could not hope to meet the required project goals by itself</u>, even if the resources used by the power system were completely freed. As a result, the concerns which drove the redesign of the electrical power system were not to free up the system resources for the purpose of meeting the project goals, per se, despite appearances to the contrary. <u>The priorities of the optimization of the electrical power system were mainly driven by the needs of the optimization of the structural system and thermal management system, instead</u>. For example, the DC-DC converters and filters used were thin, but had a large circuit footprint area in relation to their volume. This was necessitated by the need to facilitate effective thermal transfer of the heat generated by the power system out of the system, which in turn meant that the power system occupied a disproportionately large percentage of the area of the heat sink. Decreasing the footprint of the power system both meant that a smaller heat sink could be used (and thus the mass and volume of the NDL would be reduced by a correspondingly large amount), and that the physical arrangement of the components of the power system within the NDL chassis would be much more flexible. This allows (1) tighter packing of hardware (and thus vastly reduced overall system volume), (2) greater flexibility in placement of components to maximize heat transfer by eliminating “cold spots” (thereby increasing the efficiency of the thermal management system), and (3) much easier physical rearrangement of the electronics to help minimize EMI. Consequently, the results of early mechanical and thermal trade studies had a great impact on the electrical design requirements and priorities. For example, DAC 2 prioritized reducing footprint over all other considerations precisely for this reason.

Due to the considerable sensitivity of multiple components in the NDL to EMI, great effort was invested in reducing EMI. Purely electrical measures to minimize both the generation of EMI and the effect of the remaining unavoidable EMI on sensitive hardware were extensive; however, there were several cross-disciplinary efforts to reduce the effects and generation of EMI as well. Firstly, significant EMI sources – for example, the large AC current passing through the +5.5 V DC-DC converter, its load, and connecting wires – and EMI-sensitive hardware were identified. Secondly, they were physically arranged within the NDL chassis so their separation was maximized or the sensitive hardware was shielded as much as possible from the EMI. Wires that had a high potential for acting as antennas for generating or receiving EMI were either twisted together, or were noted for replacement with shielded wiring. Lastly, loads and power system components were placed such that wires which were likely to act as antennas for generating or receiving EMI were minimized in length, which in turn acts to minimize the antenna area and thus effectiveness of the antenna. This was achieved by placing loads close to their respective DC-DC converters. All of these actions required detailed knowledge of the electrical minutiae of the NDL and making informed decisions on which actions to take based on a solid understanding of the physics behind EMI, but were also bounded by what was reasonably attainable in the mechanical domain. This necessitated close cooperation during several points during the mechanical physical placement design process.

Several factors made it possible that some custom-designed converters might be rejected during test and validation. This was partially due to design requirements which were either incompletely defined and were thus not covered in datasheets, defined at such a high level that design verification was impossible short of performing test and validation on physical prototypes, or impossible to simulate. An example of this was the maximum EMI generation requirement specification. While good design practices can minimize EMI generation, it is often not characterized in datasheets and is very difficult to simulate. This was combined with a highly compressed project schedule and a budget that was constrained to only allowing a single design for each converter module to be approved for advancement to physical testing. As a result, several of the designs’ performance specifications were not possible to be verified. This made it vital that DAC 2 could handle one or more custom converter designs being rejected during test and validation. This contingency-planning was a collaborative effort that had implications for both the thermal management systems and structural systems.

From a mechanical standpoint, the main impact the DAC 2 power system had on the NDL redesign was the required minimum surface area of the heat sink. The original arrangement of the power system in the NDL had the power system concentrated in along one side, near the long edge of the heat sink. From the original power system's location, wires were run to every load in the NDL. This meant that little effort was spent on keeping loads close to their converters, and

thus keeping short wires that could act like antennas for EMI. Since the original converters worked despite this condition, the same converters should also work in the same condition inside the DAC 2 case, assuming they would fit on the surface of the heat sink. The requirement that DAC 2 had to be able to mount all DC-DC converters helped set the minimum required surface area of the DAC 2 heat sink, which was a major design constraint for the case design. This required coordination between disciplines before finalizing the initial plans for DAC 2. From a thermal standpoint, the main impact the DAC 2 power system had on the NDL redesign was that the thermal management system had to be verified to work effectively for the case of the placements and efficiencies of the worst-case scenario where all custom converter designs were rejected during validation. This required multiple simulations and trade studies, in close conjunction with alteration of placement of tightly-packed components on the DAC 2 heat sink. Since having little area to spare made rearranging components to improve thermal performance difficult, this also required close cooperation between disciplines. An analysis found a component arrangement on the DAC 2 heat sink which would permit DAC 2 to function within specification.

7. DESIGN COMPARISONS

Figure 7 From left to right, original, DAC 1, and DAC 2 designs. The approximate volumes of each are 2,200 cubic inch (original), 1,700 cubic inch (DAC 1), and 1,600 cubic inch (DAC 2).

Overall System Improvement						
	Existing Model		DAC 1		DAC 2	
	Estimate	Goal	Estimate	Reduction	Estimate	Reduction
Power	137 W	-20%	87 W	37%	76 W	45%
Mass	45 lb	-15%	35 lb	22%	32 lb	29%
Volume	2,200 in³	-20%	1700 in³	22%	1600 in³	26%

Table 1 Comparison of the original and the new designs resulting from IDEC. Volume has been approximated.

In Table 1, a mass reduction of 22% was achieved in DAC 1. This can be attributed to the use of a new heat sink design which was much smaller in size. The removal of four fans also contributed to the mass reduction. A volume reduction of 22 % was also achieved in DAC 1. This can be attributed to the placement of the new heat sink tunnel and fans within the chassis. For DAC 2, a mass reduction of 29 % was achieved. This can be attributed to a reduction in the length of the heat sink tunnel used in DAC 1, as well as a smaller case. The new case shape also allowed for a reduction in volume of 26 % for DAC 2. The reduction in power dissipation is shown as a difference of 50 W between the original (137 W) and the DAC 1 design (87 W) of the NDL. Only about 10.5 W of this was due to the optimization of the power system, which amounts to approximately 21 % of the total power dissipation reduction. This was achieved by removing

unnecessary components that were draining power for no useful return, and by replacing the most inefficient components. The reduction in power dissipation is shown as a difference of 61 W between the original (137 W) and the DAC 2 design (76 W) of the NDL. This further reduction in power draw was partially achieved through replacing components with more efficient designs, but only about 12 W of this was due to the optimization of the power system, which amounts to approximately 20 % of the total power dissipation reduction. Direct contributions to the reductions in mass and volume by the optimization of the power system were minor, due to the power system being less than 5 % of the support system's total mass and even smaller proportion of total support system volume. Thermal analysis of each design allowed for the reductions shown in Table 1 by demonstrating that the redesigns of the system would function properly in the worst case environment. Thus, thermal analysis was instrumental in the quick progression of the IDEC team's work, as it provided a rapid means of ensuring the viability of the designs.

8. CONCLUSION

The designs that compose DAC 2 still need to undergo test and validation. Once this is complete and DAC 2 is constructed, future performance optimizations of the NDL support systems' electronics beyond those outlined in DAC 1 and DAC 2 is unlikely. This is due to the fact that DAC 1 and DAC 2 specifically sought to tailor the support hardware's only significant electronics to NDL's requirements, with maximized efficiency and minimized size for the NDL's specific nominal operation state. Any future changes to the support system electronics will likely be the modification of the power system to make the EMI filter and DC-DC converters radiation-hardened and fully space-qualified. After that, the most effective course of action will likely be to optimize the mission hardware' electronics. For example, the C&DH is the highest source of power dissipation in both the DAC 1 and DAC 2 modifications of the NDL, one of the largest pieces of electronics in terms of volume, and the most sensitive in terms of radiation hardening. The mission hardware's power dissipation composes almost 80 % of the remaining power dissipation in the DAC 2 modification of the NDL. Clearly, future reductions in power consumption will have to come from mission hardware, and the C&DH looks to be the single most promising possibility. The research conducted during the project contributed to proper documentation and analysis of the existing physical chassis. Redesigns of the chassis sought the most efficient cooling system with the least mechanical complexity. All design goals were met and exceeded with clear continuation paths established. Part specification listings were created in addition to CAD model drawings with information labeled. CAD models have been archived for future reference or modification.

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